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Testing of Connectors for Cold-formed Steel Construction - Challenges, Recent Innovation, and Future Direction

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Testing of Connectors for Cold-Formed Steel Construction: Challenges, Recent Innovation, and Future Direction

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Abstract

As cold-formed steel construction continues to evolve, manufacturers are making advances in prefabricated connectors for use in a variety of applications. Often, establishing available strengths for connectors requires testing. This paper will examine some of the challenges associated with testing of these products. Available standards and criteria will be discussed, and an overview of potential difficulties with their use will be presented. Test programs conducted by one manufacturer during recent product development will be presented to illustrate some of the challenges and highlight innovations made to address them. Finally, based on experience gained through extensive testing and product development, recommendations for future direction to improve the state of the industry will be proposed.

Introduction

The use of cold-formed steel has steadily increased in recent years. With the increase in volume also has come new products and innovation in the areas of framing members, design and detailing software, and connectors. The use of connectors, and in particular proprietary connectors, has increased significantly during this time. In the not-too-distant past, connections between cold-formed steel framing members were typically accomplished either with “generic” connectors (e.g.: clip angles for stud bridging shown in Figure 1) or connections fabricated at the jobsite from standard shapes like those shown in Figure 2. Often these connections were designed based on calculations performed without standards as guidance, or simply based on acceptable performance in past applications. Little test data was available to validate design assumptions and confirm acceptable performance.

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Figure 1: Generic connector used with bridging

Figure 2: Field-fabricated curtain-wall connector

However, in recent years, stud manufacturers as well as building component manufacturers have developed products to help simplify the design and installation of connections. Some of these products are substantiated by testing, but currently there is limited design and testing guidance for manufacturers. Much is left to the product manufacturer when it comes to determining nominal, design, and allowable strengths. This paper will discuss some of the challenges that exist when developing new connector products for cold-formed steel construction. Along with these challenges also come opportunities for innovation, some examples of which will be presented. Finally, recommendations for future industry action will be presented.

Standards and Criteria

A number of test criteria exist for cold-formed steel components from organizations including AISI, ASTM, and ICC-ES. Some of the more commonly referenced documents for testing of connections between cold-formed steel structural framing members are as follows:

- AISI *Test Methods for Mechanically Fastened Cold-Formed Steel Connections* (AISI S905-08)
- AISI *Test Standard for Hold-Downs Attached to Cold-Formed Steel Structural Framing* (AISI S913-08)
- AISI *Test Standard for Joist Connectors Attached to Cold-Formed Steel Structural Framing* (AISI S914-08)
- ICC-ES *Acceptance Criteria for Connectors Used with Cold-Formed Steel Structural Members* (AC261)

- CFSEI Technical Note G100-07: *Using Chapter F of the North American Specification for the Design of Cold-Formed Steel Structural Members*

The three AISI documents listed above are for specific applications and are generally used for product testing within their respective scope. For products that are not covered by these test standards, testing is often performed in accordance with AC261, which is general in nature in order to cover a wide variety of products. AC261 incorporates the AISI test standards by reference and currently is the only criteria in the United States under which product evaluation reports are issued for cold-formed steel connector products. As a result, testing used to obtain a product evaluation report is evaluated in accordance with AC261, regardless of whether testing is performed to an AISI test standard or AC261.

Challenges and Need for Improvement

As noted above, AC261 is the primary means to obtain code approval for cold-formed steel connector products in the U.S. These evaluation reports are critical to the industry in order to create a level playing field and help ensure designers understand and properly apply data published by manufacturers. But because AC261 is used for such a wide variety of products, it is general in nature, which leads to difficulties testing products intended for specific applications. Many of the difficulties that arise can be classified under one or more of the categories outlined below.

Test Specimens and Boundary Conditions

Guidance regarding test specimen configuration and boundary conditions is unclear or incomplete. The configuration and boundary conditions of test specimens are critical to understanding and interpreting test results. In the connector industry, test specimens are often created with the intent of causing failure in the connection. Design considerations such as the shear capacity of a supported member are addressed by the designer. However, the thin-walled elements typically used in cold-formed steel construction are prone to local buckling and torsional instability, so bracing requirements and support details are critical to understanding connector performance and ensuring testing provides an accurate representation of the expected field installation.

Use of Calculations, Interpolation, and Extrapolation

Guidance on acceptable use of analysis and calculations, or interpolation and/or extrapolation of test data is lacking. Due to the high cost associated with performing physical tests, product manufacturers often look to supplement testing with analysis and calculations. It also is common practice for manufacturers to perform physical testing on conditions that bound the limits of anticipated field conditions. Guidance must be provided on how to define the critical factors to be considered when establishing these bounds, the minimum number of test conditions required within the complete range, on what basis interpolation is acceptable, and whether or not test data may be extrapolated to other conditions.

Reporting Requirements

Requirements for reporting design assumptions and testing conditions are lacking. Often, testing is specific to a particular application. However, there are no requirements to provide this information in published product data. Designers are then forced to make assumptions regarding the applicability or often are not aware that information provided may not apply to their design conditions. In some cases this may lead to inadequate designs.

Material Property Adjustments

Requirements for adjustments for material properties are unclear and potentially overly conservative. Steel used in testing almost always exceeds the minimum specified value for one or more of the critical material properties – yield stress, tensile strength, and base metal thickness. As a result, test results need to be adjusted to account for the higher material properties used in testing. In some cases, adjustments can be significant, often on the order of 20%. The proper application of adjustments is critical to ensure that designs remain safe, while avoiding overly conservative adjustments that can have a negative effect on product competitiveness.

Examples of Challenges Encountered in Testing

The authors are involved in extensive, ongoing research and product development for connectors to be used with cold-formed steel construction. During the course of testing, a number of challenges have been identified that are the result of the lack of test standards and criteria as described above. Several examples are presented below, along with some innovations used to resolve the challenges.

Out-of-Plane Loads on Bypass Curtain-Wall Slide Clips

Bypass framing is commonly used in curtain-wall construction. In many cases, slide clips are used to allow relative vertical movement between the curtain-wall system and the supporting structure. These connectors must transfer out-of-plane wind and seismic loads from the curtain wall to the main structure. For proprietary connectors, these loads are typically established through some sort of test program. However, the extent of testing required is not well defined.

In one testing scenario, connectors are tested on a thick material to determine the connector strength. The available strength for installations on thinner materials is then established using a simple calculation of the fastener strength, limited to the maximum tested value. This approach may seem reasonable, but there are several shortcomings.

First, this approach does not properly account for eccentricities inherent in these connectors. Many bypass connectors consist of an outstanding leg that is attached to the supported stud and an anchor leg for attachment to the structure that is oriented perpendicular to the outstanding leg. In the case of a load in the outward direction, fasteners in the anchor leg must resist the applied load. Since the anchor fasteners are typically eccentric to the outstanding leg, prying forces are developed. Calculations typically do not consider these forces and if attempts are made to include them in calculations, they are difficult to determine accurately. If ignored or incorrectly determined, inaccurate connector strengths will be determined.

A second concern is whether or not AISI calculations accurately capture the behavior of fasteners in these connectors. Slide clips typically involve a screw fastener installed through a slot to attach the connector to the framing member and provide relative movement capability. Based on observations during testing, behavior is often controlled by tilting of these screws. In many cases, failure occurs when the slot deforms, allowing the head of the fastener to pull through the slot. AISI equations for connection shear limited by tilting and bearing do not consider screws installed in slots and appear to over estimate the capacity in these conditions. Furthermore, tilting behavior becomes less significant when connectors are attached to thicker studs, so use of such tests as an upper bound may be misleading.

With this understanding, an extensive and rigorous test program was undertaken during product development. Testing included every connector model and installations on all stud gauges for which data is published. Although all conditions were not tested, the depth and breadth of testing allowed for the generation of complete data substantiated by testing.

Vertical Loads on Bypass Curtain-Wall Fixed Clips

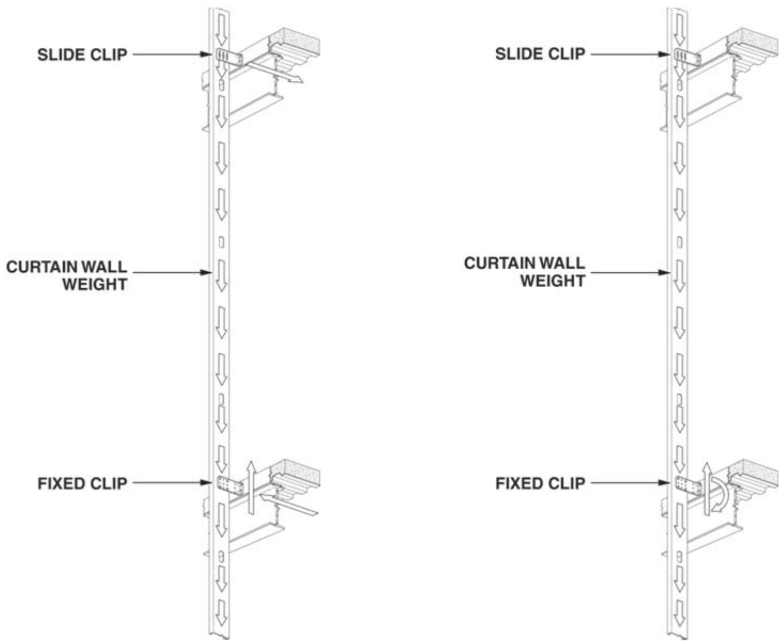
As mentioned previously, bypass framing is common for curtain-wall construction. In this type of framing, metal studs run continuous past the edge of the floor slab and are hung off the outside of the main building structure. Connectors referred to as fixed clips are used to support the weight of the curtain-wall system in elevated conditions.

In bypass framing the weight of the curtain wall is eccentric to the connector attachment to the main building structure. In order to resolve the moment created by this eccentricity, reactions other than a vertical shear are required. But bypass curtain wall-systems are often indeterminate, so the distribution of forces to resist the moment caused by the eccentricity cannot be determined until the details of the installation are known. However, installations can be configured from nearly endless combinations of stud size and gauge, connector size and fasteners, number and length of stud spans, and support conditions at the main building structure.

In a typical bypass framing condition, the relative stiffness of the elements will determine if the moment from the eccentric weight is resolved as a horizontal force couple at different connection points (see Figure 3a), a moment in the anchorage between the connector and the structural frame (see Figure 3b), or a combination of the two. Figure 4 shows the forces acting on the fixed connectors for the two conditions shown in Figure 3. These clearly illustrate that the available strength to carry vertical load will be quite different for the two conditions as well as for conditions that lie between these extremes. In addition, design of anchorage that is often required will vary drastically depending on the loads transferred at the face of the supporting structure.

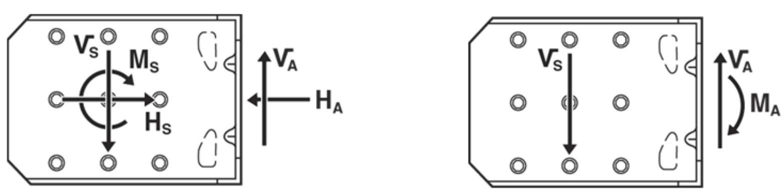
Product manufacturers strive to provide simple-to-use product data that covers a range of conditions. Tabulating available strength as a single vertical load value is convenient, but is limiting since any such value is inherently tied to a specific installation. Designers routinely encounter conditions that vary within the range of those described, so a more comprehensive solution was sought. But based on discussions above, it is clear that the possible conditions vary too widely to allow comprehensive testing. The elastic vector or instantaneous center methods may be used to perform calculations for a range of conditions, but such an approach would not be confirmed by testing. In addition, calculated results would be based on specific load distributions with no way to correlate them to any particular field installation.

To address these challenges, a two-phase testing program was conducted. In the first phase, a test setup was devised that included a flexible support condition in conjunction with extremely stiff framing, resulting in loads similar to the idealized condition depicted in Figures 3a and 4a. This setup is critical for the connection between the connector and stud since it results in the maximum moment in the fastener group attaching the connector to the stud for a given applied vertical load. This testing was used to establish what are referred to as allowable *connector* loads.



(a) Horizontal force couple (b) Moment at anchorage

Figure 3: Possible resolution of eccentric weight in bypass curtain wall



(a) Horizontal force couple (b) Moment at anchorage

Figure 4: Forces on fixed-clip connectors due to eccentric weight

In the second phase, the idealized condition shown in Figures 3b and 4b was tested by simply attaching a connector to the supporting structure and loading as a cantilever beam. This condition results in the maximum moment at the connection to the structure for a given vertical load and is critical for this anchorage connection. Loads from these tests are used to establish allowable *anchorage* loads. With this strategy, the designer simply needs to select the lower of the allowable connector load and allowable anchorage load for the given design conditions. The result is design values that can be used without the need for modification for most practical installations.

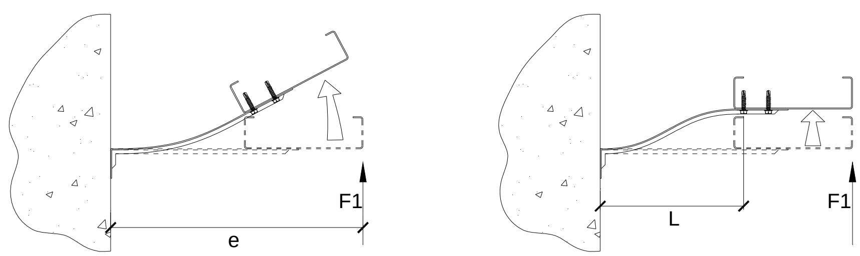
In-Plane Loads for Bypass Curtain-Wall Connectors
For curtain-wall designs involving seismic loading, transferring in-plane loads from the curtain-wall system to the supporting structure is an important design consideration. In many cases, this transfer of load is accomplished by using slide-clip and fixed-clip connectors like those discussed previously. Similar to vertical loads for fixed clips discussed above, the capacity to resist in-plane loads varies widely based on the details of installation.

The capacity of these connectors to resist in-plane loads is heavily dependent on the degree of fixity at each end of the clip. Figure 5 shows two possible ways a bypass connector can deform due to a load applied in the plane of the wall, depending on the amount of fixity present. In Figure 5a, the connector deforms as a cantilever. For an available bending strength of the connector equal to M_c, the strength to resist in-plane loads, F1, is simply

$$F1 = M_c/e$$

In Figure 5b, the connector deforms in double curvature and the available in-plane strength is

$$F1 = 2M_c/L$$



(a) Cantilever (b) Double curvature

Figure 5: Deformation of bypass connectors resisting in-plane loads

It is a simple matter to devise testing to simulate each of these conditions. In the first case, connectors can be attached to a support and loaded as a cantilever. In the second case, connectors can be attached to rigid supports and forced to deform in double curvature. Obviously, testing of the same connector under these two conditions will result in significantly different in-plane strengths. Typical field conditions likely lie somewhere between these idealized extremes, so testing based on the cantilever condition will be overly conservative for many cases. Conversely, tests for the fixed condition represent capacities that may never be developed in actual practice.

To address this challenge, testing is being conducted using a system approach. In these tests, installations that mimic field conditions are tested and include multiple studs, each with a connector, and sheathing attached to the framing. In these tests, true boundary conditions and the associated degree of fixity are created. The result is available strength values that can be used directly by designers with confidence for a given type of installation.

Head-of-Wall Connector Testing

Head-of-wall connectors are frequently used at the top end of studs to allow relative vertical movement between the stud and structure above, while still providing lateral support. It is common in the connector industry to perform testing in a manner that forces the test failure into the connector in order to define the connector capacity. It is then up to the designer to check other design considerations, such as stud shear strength, flexural capacity, etc. However, in the case of head-of-wall connectors, this can create problems.

In typical installations, fasteners are installed through the connector, close to the end of the stud. Tests conducted with this condition show that ultimate test loads on thinner studs are sometimes controlled by failure of the web (see Figure 6). Tests run on the same installation with the stud extended beyond the connection point show a substantial increase in strength and a shift in the failure mode to fastener tilting and bearing (see Figure 7). Typical practice would be to report the higher strength values for the connector, but checks reveal that the failure modes observed in testing are not well predicted by available AISI design equations. In particular, web crippling equations assume bearing conditions and cannot be directly applied to fastener connections. In addition, attempts to apply shear design equations to the connection did not correlate well with testing.

Based on this knowledge, testing was performed that represents a departure from typical connector testing protocol. Instead of performing tests to maximize the connector ultimate loads, testing was performed using an installation similar to that shown in Figure 6. This testing captured the failure modes described above that cannot readily be calculated by designers. The resulting test loads are lower than a more typical test program would have yielded, but the data generated considers the installed performance and provides designers with design values that can be used directly without overestimating available strengths.

Figure 6: Photo of web failure from head-of-wall connector test

Figure 7: Photo of head-of-wall connector test with extended stud

Bridging Connector Testing

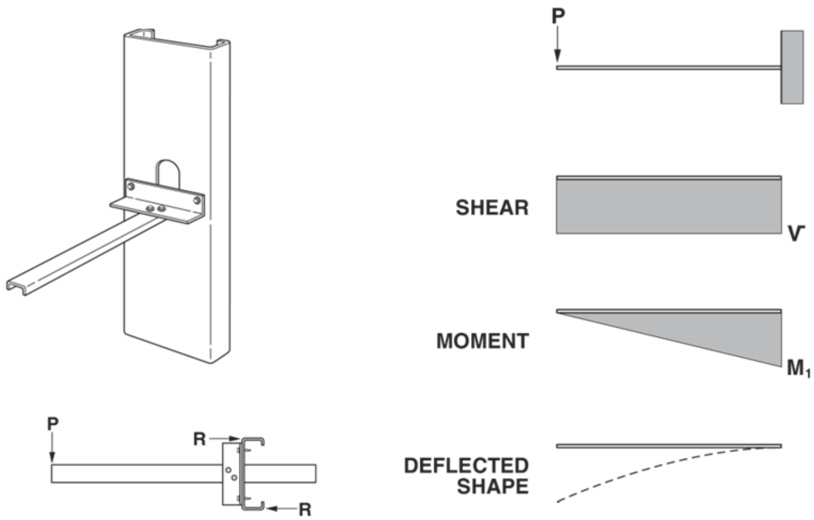
Bridging connectors are used in stud-wall construction to restrain twisting from loads applied in the plane of the web and restrain lateral translation for bracing of compression members. Connectors are most often used in conjunction with 1-1/2” U-channel installed through the web punch-out of studs.

For flexural members, AISI S100 includes strength requirements for restraint against twisting. The rotational strength of connectors to resist twisting can be established through testing. Guidance on testing can be obtained from AISI Research Report *Bracing Requirements of Cold-Formed Steel Cee-Studs Subjected to Axial Compression* (RP04-1), which forms the basis of the bracing requirements contained in the 2007 edition of AISI S100. However, tests conducted with similar test setups revealed shortcomings.

The test setup as described in AISI RP04-1 is a cantilever setup. A section of U-channel is attached to the web of a stud using a connector, and lateral load is applied to the channel. A schematic of the setup is shown in Figure 8a, and the resulting U-channel shear and moment diagrams and deflected shape are shown in Figure 8b. Testing with this setup revealed that in some cases, the U-channel will fail in flexure before the connector reaches its ultimate load. Calculations show that the bridging connector capacities obtained from these tests are not adequate to develop the bracing demands required under high lateral pressures. Upon further review, it became evident that this was a limitation of the test setup.

Figure 9 provides a sketch of a typical wall system subject to lateral load and braced by U-channel with bridging connectors. The moment diagram reveals that the maximum moment in the U-channel, M_1, is half that resisted by the connector, M. However, as shown in Figure 8b for the cantilever test setup, the maximum moment in the U-channel is equal to the moment in the connector.

Therefore, to obtain the same load in the connector, the cantilever test setup requires twice the moment in the U-channel compared to the installed condition. Clearly, premature flexural failure of the channel is a concern with this test setup.



(a) Schematic of test setup

(b) U-channel shear, moment, and deflected shape

Figure 8: Cantilever test setup for bridging connectors

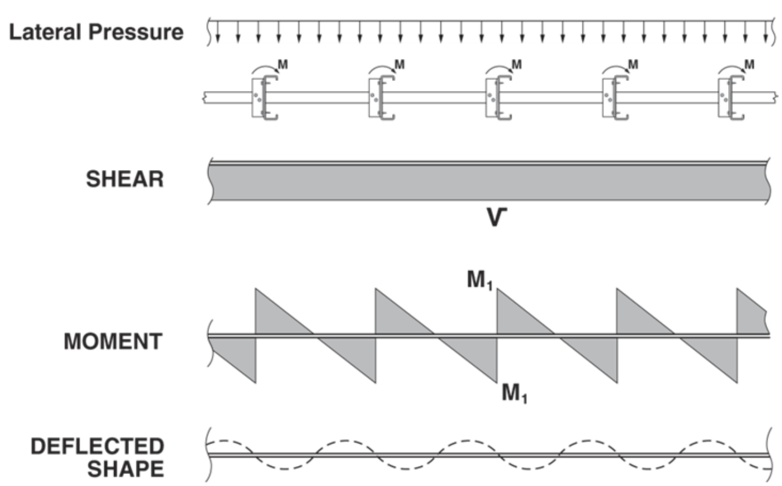


Figure 9: Typical wall system subjected to lateral load

An alternate test setup that eliminated the limitation discussed above was eventually developed. The alternate test setup was devised with the intent of matching the shears, moments, and deflected shape shown in Figure 9. By examining the diagrams between the mid-points of adjacent stud bays, a sub-assembly for the test setup as shown in Figure 10 was established.

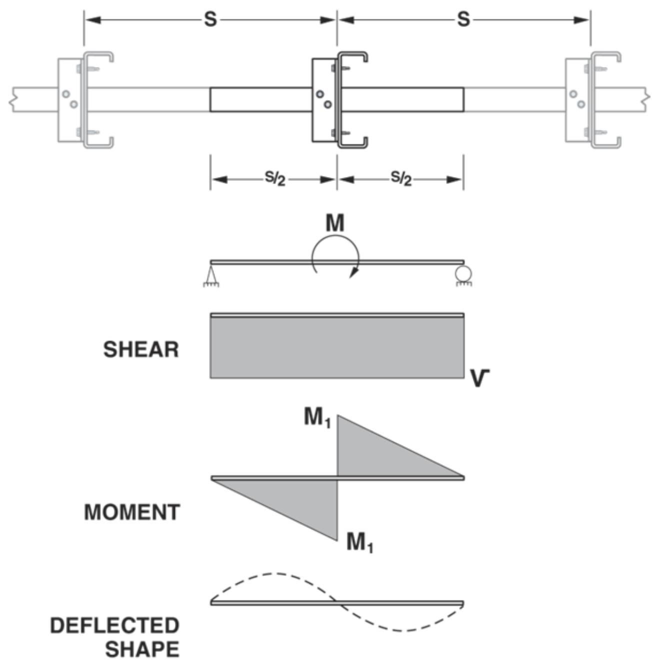


Figure 10: Sub-assembly for bridging connector testing

One challenge encountered was to construct a test fixture that permitted application of a moment, while not introducing additional boundary conditions. In order to accomplish this, a moment was applied as equal and opposite uniform loads on the stud flanges. Figure 11 shows a schematic of the idealized test setup. The inherent flexibility of the system created another challenge, requiring that a setup be devised that could accommodate large rotations and deflections without altering the overall test geometry. For example, under large rotations, the horizontal and vertical distances between points may change. But in a test where these points are used to calculate moments, special precautions need to be taken.

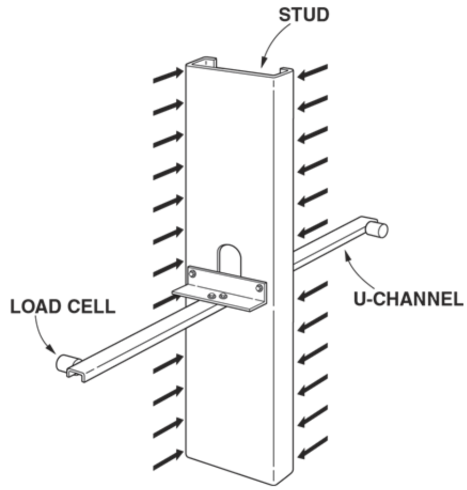


Figure 11: Idealized test setup for bridging connectors

Several different test fixtures were constructed and tests were run. Tests were instrumented with multiple load cells in order to confirm assumed force distribution. In some cases, the sum of reacting loads was not equal to the input load, meaning that load was being lost through friction. After extensive finite element analysis and physical testing of various test setups, an innovative proprietary solution was found that minimizes losses through friction and yields consistent results.

Suggested Improvements

The discussion above clearly illustrates some of the problems with using current criteria to evaluate a range of cold-formed steel connector products. Based on review of current standards and criteria as well as extensive testing, it is suggested that test standards and/or acceptance criteria be developed that are specific to the unique design considerations of cold-formed steel applications. Some of the recommended items to be considered in such documents include the following:

- Provide guidance on testing required, including:
    - Strength, deflection, and other serviceability tests
    - Test specimen configuration (bracing, supports, etc.)
- Provide guidance on processing of test data, including:
    - Interpolation and extrapolation of test results

    - Adjustments for material properties
- Establish consistent reporting requirements for test results, such as:
    - Limitations and identification of calculated items
    - Design assumptions appropriate for test setups used

Note that although it is important to establish such standards to bring consistency and reliability to the cold-formed steel connector industry, it is equally important that they do not limit the opportunity for innovation. Striking a balance between these seemingly competing objectives will be difficult.

Conclusions

Manufacturers of connector products for cold-formed steel construction are provided with only general guidance for testing new products. The current standards and criteria are not adequate to support the continued growth of the cold-formed steel market and the resulting product innovation. In particular, standards are required that are tailored to specific applications. Such guidance will level the playing field, resulting in more consistent and reliable information for designers and a means by which code compliance can be confirmed for specific products. However, the challenge is to avoid creating standards that are too restrictive and limit possibilities for continued innovation.

Notation

e	=	eccentricity from face of support to center of mass of curtain wall
F1	=	lateral load in the plane of a curtain wall
H_a	=	horizontal reaction at connector anchorage
H_s	=	horizontal force at connector-to-stud fastener group
L	=	distance from face of support to point of fixity in double curvature bending
M	=	moment in bridging connector resulting from torsion in stud
M_1	=	maximum moment in bridging U-channel
M_a	=	moment reaction at connector anchorage
M_c	=	out-of-plane flexural strength of bypass connector
M_s	=	moment at connector-to-stud fastener group
P	=	applied load in bridging connector test
V	=	shear in bridging U-channel
V_a	=	vertical reaction at connector anchorage
V_s	=	vertical force at connector-to-stud fastener group

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